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Changes identification of the Three Gorges reservoir inflow and the driving factors quantification

Yu Zhang [a], Ping-an Zhong [a, b, *], Manlin Wang [a], Bin Xu [a], Juan Chen [a]

[a] College of Hydrology and Water Resources, Hohai University, No. 1 Xikang Road, Nanjing 210098, China
[b] National Engineering Research Center of Water Resources Efficient Utilization and Engineering Safety, Hohai University, No. 1 Xikang Road, Nanjing 210098, China

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ABSTRACT

The study on runoff series variation is of great significance for the development and utilization of water resources in a river basin. In this paper, runoff series data from the Three Gorges reservoir and five upstream catchments observed from 1951 to 2013 are used to analyze the changes in the Three Gorges reservoir inflow series via the Mann–Kendall test. Based on the hydro-metrological data (i.e. precipitation, and temperature) and the human activities data (i.e. urbanization percentage, effective irrigation area, afforestation area, population, and gross domestic product (GDP)) during the same period, the back-propagation artificial neutral network (BP-ANN) model is applied to quantify the influence of the driving factors. The results show: (1) During the study period, there is a significant decrease in the Three Gorges reservoir inflow and the reduction rate is 0.73 mm per year; (2) Runoff from all of the five upstream catchments of the Three Gorges reservoir decrease. Specifically, the decreased trends in the runoff from the Mintuo River catchment and the Jialing River catchment are statistical significant; (3) Impacts of climate change and human activities on changes in the Three Gorges reservoir inflow series account for 36% and 64%, respectively. Among all the driving factors, the precipitation is the dominant influencing factor, accounting for the relative contribution of 25%. The temperature, urbanization percentage, effective irrigation area, population and GDP are the minor factors, accounting for the relative contributions of 11%, 17%, 15%, 15% and 14%, respectively. The afforestation area is the least effective factor with a relative contribution of 3%.

1. Introduction

Influenced by both climate variability and human activities, the uncertainty level of water resources deepens (Milly et al., 2005). Identifying the change rules of water resources under the changing environment and quantifying the influence quantities of their driving factors become the focus of research in water science. It is also important for water resources planning and management in the basin.

Runoff changes are response to the combined effects of climate change and human activities. When climate change and human activities intensify abnormally, the hydrological processes in the basin will change more obviously (Schindler, 2001). Sensitivity of runoff to climate change in different basins around the world has been studied, and the impacts of climate change on runoff have been analyzed (Nash and Gleick, 1991; Sankarasubramanian et al., 2001; Chiew, 2006; Jones et al., 2006; Fu et al., 2007). Scientists have also studied the law of runoff changes caused by human activities. Water resources consumption due to human life and production can also cause runoff reduction (Tao et al., 2011). Besides the direct water-related activities, the intensity and large scale of land use and land cover changes have profound impacts on runoff among all the human activities factors (Zhang et al., 2008; Zheng et al., 2009). For example, afforestation can lead to a decrease in runoff (Brown et al., 2005; Lane et al., 2005). The water bodies, vegetation, bare land changes can also cause the changes in hydrological cycle and lead to runoff changing (Zhang et al., 2001; Scanlon et al., 2007; Yang and Tian, 2009).

The joint impacts of climate change and human activities on runoff have received global attention (Siriwardena et al., 2006; St. Jacques et al., 2010; Alkama et al., 2011; Oberhansli et al., 2011). In China, the rapid development of industry and agriculture in recent decades coupled with temperature and precipitation

* Corresponding author. College of Hydrology and Water Resources, Hohai University, No. 1 Xikang Road, Nanjing 210098, China.
E-mail addresses: zhangyu74@163.com (Y. Zhang), pazhong@hhu.edu.cn, zhongpahhu@163.com (P.-a. Zhong), manlin220@163.com (M. Wang), binxuhhu@gmail.com (B. Xu), chenjuanhhu@163.com (J. Chen).

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variations (Piao et al., 2010), the impacts of climate change and human activities on hydrological cycle and water resources of major river basins have received more attention (e.g. Liu et al., 2010; Jiang et al., 2011; Zhou et al., 2012; Wang et al., 2013; Dong et al., 2014; Chang et al., 2015). Nonetheless, quantifying the influence of climate change and human activities on runoff changes is still a challenge. So far, the commonly used methods are the climatic elasticity method, the hydrological sensitivity analysis method, the hydrological model method, etc.

The climatic elasticity method and the hydrological sensitivity analysis method belong to statistical methods. The climatic elasticity method which was first proposed by Schaake (1990) has been continually extended and improved (e.g. Fu et al., 2007; Yang and Yang, 2011). Besides, the hydrological sensitivity analysis method proposed by Dooge et al. (1999), was adopted to identify the effects of precipitation variation and potential evaporation variation on runoff. It has also been applied to distinguish impacts of climate change and human activities on runoff. The hydrological model methods including the lumped hydrological model method and the distributed hydrological model method are different from the statistical methods. They are partly or wholly based on physics. The detailed information of these commonly used methods including central mechanism, advantage, disadvantage and several related studies are given in Table 1.

Table 1
Characteristics of commonly used methods.

Method		Central mechanism	Advantage	Disadvantage	Study
Statistical method	Climatic elasticity method	The climate elasticity of runoff can be defined by the proportional change in runoff divided by the proportional change in a climatic variable such as precipitation. The precipitation elasticity of runoff was thus expressed as: $\Delta Q_i/\overline{Q} = \varepsilon_P \cdot \Delta P_i/\overline{P}$ where ΔQ_i and ΔP are changes of the annual runoff and the precipitation with respect to long-term average of runoff $\overline{Q}$ and precipitation $\overline{P}$, respectively	The statistical method is easy to use and has less critical requirement of data sets.	The statistical method is based on data. It can only calculate the impact of climate on runoff and then attribute the rest to human activities.	Fu et al., 2007 Zheng et al., 2009 Ma et al., 2010 Yang and Yang, 2011 Wang et al., 2013
	Hydrological sensitivity analysis method	$\Delta Q_C = \beta\Delta P + \gamma\Delta PET$ $\Delta Q_H = \Delta Q - \Delta Q_C$ where ΔQ is combination of climate change and human activities; ΔQ_C is the change of runoff induced by climate change only; ΔQ_H is the change of stream discharge caused by human activities only; β and γ are the sensitivity coefficients of runoff to precipitation and PET, expressed as: $\beta = (1+2x+3wx)/(1+x+wx^2)^2$ $\gamma = -(1+2wx)/(1+x+wx^2)^2$ where w is calibrated by comparing the long-term annual AET, x is the mean annual index of dryness.			Jones et al., 2006 Li et al., 2007 Ma et al., 2008 Zhang et al., 2008 Liu et al., 2009 Zhao et al., 2010 Jiang et al., 2011 Wang and Hejazi, 2011 Wang et al., 2013 Zuo et al., 2014
Hydrological model method	Lumped hydrological model method	The hydrological models are calibrated and validated using data during baseline period. Then the models are run using climate during altered period with human activities and during baseline period. ΔQ_C is estimated as the	This method uses simple laws and assumptions to understand hydrological characteristics.	This method considers the whole basin as a whole, which does not consider the spatial variation of the basin. The parameters in the models are mostly based on empirical formulae which lack explicit physical meaning.	Wang et al., 2013 Zeng et al., 2014 Zuo et al., 2014
	Distributed hydrological model method	difference of the simulated runoff during altered period than the simulated runoff during baseline period, whereas, ΔQ_H is estimated as the difference of the simulated runoff during altered period than the observed runoff during altered period.	This method considers the spatial variability of hydrological process and describes the mechanism of hydrological process more accurately. It cannot only simulate the hydrological response caused by climate change, but also simulate the hydrological response caused by land use and land cover change.	This method is always limited due to the time-consuming calibration and validation process, requirement of large data sets and complexity and uncertainty in model structure and parameter estimation.	Guo et al., 2008 Jiang et al., 2011 Zhang et al., 2012 Li et al., 2013 Dong et al., 2014 Chang et al., 2015 Heo et al., 2015